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Development perspectives on aquatic ecology and management options for the Lower Lobau

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The urban floodplain Lobau within the city limits of Vienna has been affected by the Danube regulation in the late 19th century leading to changes in the aquatic habitat composition and a reduced water exchange with the riverine main channel. As a consequence of the regulation, sedimentation and terrestrializiation processes prevail. Still, the Lower Lobau remained as a green space, in contrast to the Upper Lobau, where settlements and agricultural area increased since the late 19th century. While the Lobau harbors a rich aquatic biodiversity and is part of the Danube Floodplain National Park, the high biodiversity and large number of protected species (e.g., high number of macrophyte species and amphibian species) as well as the ecological conditions of the surface and the groundwater system are threatened due to declining water levels, and fragmentation of waterbodies. In 2015, analyses of the potential effects of management scenarios to improve the water supply (S3 = constant water supply from the New Danube) and the dynamic water exchange (S20 = dynamic water supply) with a business as usual scenario (S0 = no extra water supply to the Lower Lobau) showed clear risks of S0 leading to a further decline of available habitats for various species, deteriorating the ecological conditions further. Scenario S3 will establish higher water levels in the floodplain system and can support the communities currently present, while the S20 would introduce dynamic water exchange conditions with the riverine main channel and allow an additional establishment of rheophilic communities, especially supporting a more diverse fish community. These analyses back in 2015 have not considered effects of climate change enhancing the drying of the floodplain systems. The current alarming situation in the floodplain systems of the Lower Lobau urges to take immediate actions in counteracting the loss of waterbodies and decline of surface water and groundwater levels considering new sources for water enhancement schemes and solving existing conflicts with drinking water production in terms of potential water quality risks.

Hein T, Bondar-Kunze E, Feldbacher E, Funk A, Graf W, Griebler C, Haidvogl G, Hohensinner S, Weigelhofer G (2023) Entwicklungsperspektiven zu Gewässerökologie und Managementoptionen für die Untere Lobau.
Die Lobau innerhalb der Stadtgrenzen von Wien ist stark von der Donauregulierung im späten 19. Jahrhundert betroffen, die zu einer Veränderung in der Zusammensetzung der aquatischen Lebensräume und zu einem verringerten Wasseraustausch mit dem Hauptstrom geführt hat. Als Folge der Regulierung herrschen Sedimentations- und Verlandungsprozesse vor. Dennoch ist die Untere Lobau als Naturraum erhalten geblieben, im Gegensatz zur Oberen Lobau, die seit dem späten 19. Jahrhundert immer mehr in Siedlungs- und Landwirtschaftsflächen umgewandelt wurde. Obwohl die Lobau eine reiche aquatische Biodiversität beherbergt und Teil des Nationalparks Donau-Auen ist, sind die hohe Biodiversität und die große Anzahl geschützter Arten (z. B. eine große Anzahl von Makrophyten- und Amphibienarten) sowie die ökologischen Bedingungen des Oberflächen- und Grundwassersystems durch sinkende Wasserstände und die Fragmentierung der Gewässer bedroht. Analysen der potenziellen Auswirkungen von Managementszenarien zur Verbesserung der Wasserversorgung (S3 = konstante Wasserzufuhr aus der Neuen Donau) und des dynamischen Wasseraustauschs (S20) mit einem Business-as-usual-Szenario (S0 = keine zusätzliche Wasserzufuhr in die Untere Lobau) im Jahr 2015, ergaben ein eindeutiges Risiko, dass S0 zu einem weiteren Rückgang der verfügbaren Lebensräume für verschiedene Arten führt und die ökologischen Bedingungen weiter verschlechtert. Das Szenario S3 führt zu höheren Wasserständen im Auensystem und kann die derzeit vorhandenen Lebensgemeinschaften

erhalten, während S20 einen dynamischen Wasseraustausch mit dem Hauptgerinne initiiert und eine zusätzliche Etablierung von rheophilen Lebensgemeinschaften ermöglicht, die insbesondere durch eine vielfältigere Fischgemeinschaft gekennzeichnet sind. Bei diesen Analysen aus dem Jahr 2015 wurden die Auswirkungen des Klimawandels, der die Austrocknung der Auensysteme verstärkt, nicht berücksichtigt. Die derzeitige alarmierende Situation in den Auensystemen der Unteren Lobau macht es dringend erforderlich, sofortige Maßnahmen zu ergreifen, um dem Verlust von Gewässern und dem Rückgang des Oberflächen- und Grundwasserspiegels entgegenzuwirken, indem neue Möglichkeiten für Maßnahmen zur Kompensation des Wasserdefizits in Betracht gezogen und bestehende Konflikte mit der Trinkwassergewinnung im Hinblick auf potenzielle Wasserqualitätsrisiken gelöst werden.

Keywords: floodplain, Lobau, fragmentation, decreasing water table, biodiversity, management scenarios.

Floodplain status worldwide and along the Danube

Worldwide, riverine floodplains have been decoupled from riverine dynamics and exposed to land use changes, dramatically declining in their areal extent (Tockner & Stanford, 2002). These alterations have severe implications on the biodiversity of riverine landscapes and the various ecosystem services provided by floodplains (Tomscha et al. 2017). Hydromorphological alterations, such as channelization, flood protection, river straightening, and land-use changes, as well as pollution have further impacted the ecological status of floodplains in the Danube River basin (Habersack et al. 2016; Tschikof et al. 2022). As a consequence, almost 80 % of former floodplain areas along the Danube River have been disconnected from the main river and converted to arable land and settlements, leading to severe reductions in their multiple ecological functions and the provision of ecosystem services (Hein et al. 2016; Stammel et al. 2018; Funk et al. 2019). Large-scale conservation and restoration actions are required to maintain and restore the integrity and multifunctionality of river floodplains in the Danube basin, especially focusing on biodiversity and the provision of ecosystem services (Funk et al. 2021; ICPDR 2021).

Basin-wide conservation and restoration efforts demand the assessment and further implementation at regional scales, especially in the Upper Danube reach, which currently shows the largest loss of intact floodplains (Hein et al. 2016). The Lobau, an urban floodplain within the city limits of Vienna and part of the Danube Floodplain National Park, is an example of such a highly degraded and widely used Danube floodplain. Especially the downstream part of the Lobau, the Lower Lobau, harbors (still) a high diversity of partly rare and protected plants and animal species and thus urgently deserves science-based discussions about potential measures and ways to solve current conflicts of uses (Sanon et al. 2012). A long-term interdisciplinary research project (2005-2015) provided predictions on the ecological, hydrological, and hydro-chemical development of the floodplain related to different hydrological management options (scenarios). One final outcome of the project was the identification of conflicts between the drinking water production and the ecological state of surface waters in the Lower Lobau (Sanon et al. 2012; Preiner et al. 2018), while other uses were not further investigated in the frame of this project (e.g., recreational uses). The main reasons for the current prohibition of surface water supply or reconnection measures are the suspected negative effects of the increased surface water-groundwater interactions on the quality of the groundwater used for drinking water production. Thus, no measures have been taken since the interdisciplinary project was finalized seven years ago (Trauner et al. 2016).

So far, no strategy to solve this conflict has been developed, while the ongoing climate crisis has further deteriorated the ecological status of the Lobau. In this article, an overview on the current ecological status and potential measures to improve the ecological conditions of the aquatic ecosystems are discussed and recommendations for urgent management actions are given. Aspects of terrestrial ecology are not considered in this article.

The Lobau Floodplain before and after the Danube regulation

Prior to the large river regulation in the 19th century, the Austrian Danube represented a gravel-dominated, laterally active anabranching river (Nanson & Knighton 1996) characterized by distinct fluvial dynamics and a combination of braiding and sinuous-meandering channels in the alluvial sections. Floodplains in the middle Danube reaches, such as the Lobau, were primarily built up of loosely deposited gravel and compact fine sediments (Nanson & Croke 1992; Hohensinner et al. 2022; Fig. 1). Channel shifts and cutting off of river bends were typical natural processes in the dynamic areas of the Danube, leading to the ongoing emergence of new habitats and transformation of existing habitats (Hohensinner et al. 2008). However, historical analyses show that the Lobau also had several stable areas over extended time periods which were characterized by siltation and ecological succession of aquatic and terrestrial habitats.

One specific geomorphological "hot-spot" was crucial for the evolution of fluvial landforms in the Lobau. At the upstream end, where the tectonic subsidence ultimately reaches

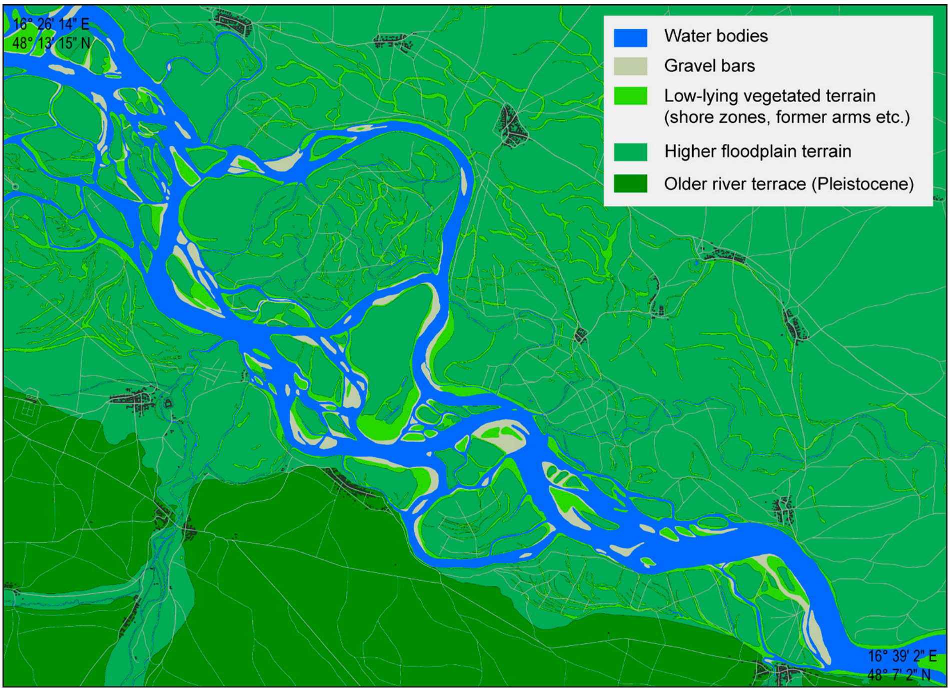

Fig. 1: Danube river landscape in the Lobau downstream of Vienna in 1726 (black dots: settlements; Eberstaller-Fleischanderl et al. 2004). – Abb. 1: Donau-Flusslandschaft in der Lobau stromabwärts von Wien 1726 (schwarze Punkte: Siedlungen; Eberstaller-Fleischanderl et al. 2004).

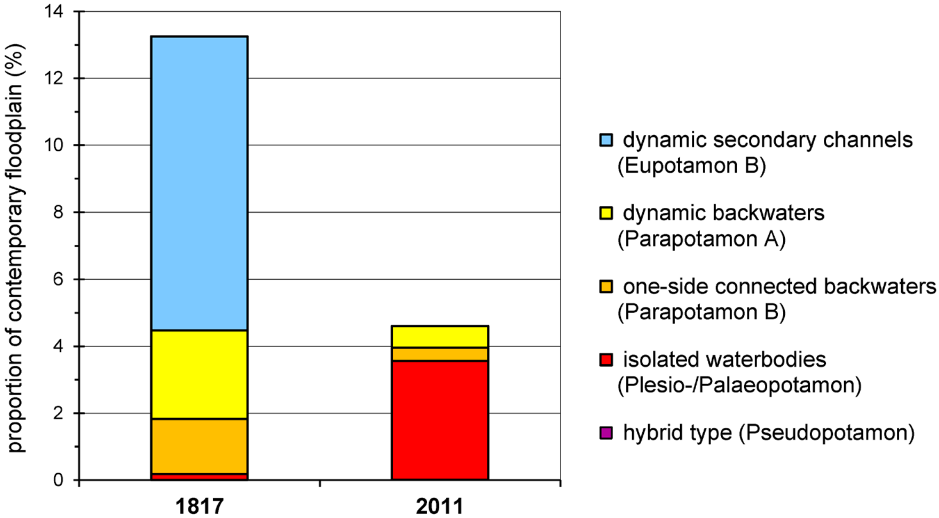

Fig. 2: Waterbody types in the Lower Lobau 1817 and 2011 (area shares in % of the contemporary floodplain that was formed in the last 500 years; Pseudopotamon is not visible due to minor areal extent; for definition of waterbody types see Hohensinner et al. 2011). – Abb. 2: Gewässertypen in der Unteren Lobau 1817 und 2011 (Flächenanteile in % des neuzeitlichen Augebiets, das in den letzten 500 Jahren entstanden ist; Pseudopotamon ist aufgrund der geringen Flächenausdehnung nicht sichtbar; zur Definition der Gewässertypen siehe Hohensinner et al. 2011).

5,500 m below the current terrain surface (Schwechat Tief, Schwechat subsidence), a significant reduction in channel slope existed prior to the river regulation (Lorenzo 1819), leading to amplified fluvial dynamics (deposition and remobilization of sediments) and the formation of ice jams (Hohensinner & Pöppl 2022). Here, the floodplain was one of the broadest along the Austrian Danube River section. Around 1817, the (almost) permanently flowed through secondary channels amounted to 66 % of the total floodplain waterbodies (without the main river channels) or 8.8 % of the contemporary floodplain extent of the Lower Lobau, respectively (Fig. 2; the contemporary floodplain refers to the part of the river landscape that was formed under the climatic-hydrological conditions of the modern period since approximately AD 1500). Other types of backwaters were much less frequent (Hohensinner & Jungwirth 2009; Graf et al. 2013).

The first large river regulation in the Lobau was completed in 1836, when a two-kilometer long cut-off was created to shorten a river bend close to Fischamend and Schönau. In the following years, training walls and embankments were constructed along the main channel to improve navigation and prevent ice jam formation (Donau-Regulierungs-Commission 1850). After the termination of the Viennese river regulation program around 1880, the Marchfeld flood protection levee was extended further downstream through the Lobau. This measure resulted in the separation of large parts of the floodplain from the river. Currently, the Lobau is only connected with the Danube at the downstream end (Schönauer Schlitz; Reckendorfer et al. 2013; Weigelhofer et al. 2015).

The various human interferences altered the composition of water bodies in the Lobau (Fig. 2). As many lotic secondary channels were cut off at their upstream ends, one-side connected backwaters increased. In 1875, at the end of the Viennese Danube regulation program, the backwaters already showed a larger aerial expansion than the main channel, indicating an entirely unnatural hydro-morphological configuration. As a consequence of the progressive channelization and associated terrestrialization processes, the area of dynamic and one-side connected backwaters significantly declined, while isolated backwaters drastically increased in numbers (Fig. 2). In 2011, water bodies in the Lower Lobau only showed 35 % of their historical extent in 1817 (calculated without main channel, tributaries and the Lobau Harbour). While originally dynamic secondary channels have vanished, isolated water bodies dominate today.

The loss of water bodies in the Lobau floodplain, especially that of small and shallow ones, is still ongoing and will continue in the future if no measures are taken. Sedimentation rates of more than 40 cm until 2050 are predicted in stagnant backwaters near the inflow of the Danube into the Lobau due to fine sediment inputs from the Danube during flooding (Funk et al. 2014; Weigelhofer et al. 2015). In more distant isolated water bodies, sedimentation rates of up to 15 cm are expected due to primary production until 2050. Increasing and prolonged drought periods, going along with receding surface and subsurface water levels, will aggravate the situation further (Kling et al. 2012).

Land use and ecosystem services

While most areas of the former Viennese Danube floodplains were turned into residential areas, the Lobau remained as a green space. This was partly owed to the integration of the Lobau in the “Wiener Wald- und Wiesengürtel”, a green belt established around the city in 1905, to improve among others the air quality in the industrializing city. Another reason was the accessibility of the area, as in the beginning 20th century Lobau was not yet connected to the public transport network. But these circumstances did not prevent the area from various human uses which diversified and intensified especially during the 20th century.

Forestry and hunting were dominating uses in the whole area of Lobau over centuries. After 1918, the Upper and the Lower Lobau experienced different developments (Fig. 3). As the Upper Lobau was closer to the city of Vienna, especially agricultural areas increased considerably to more than 30 % of the total area. The total expansion of settlements in the 1920s and 1930s is difficult to estimate as with one exception (Biberhaufen; Eder & Eichert 2005) most of the settlements evolved without formal permission. However, the municipality tacitly accepted also these buildings and vegetable gardens because of the economic crises and the shortage of food for the Viennese population after World War I. In 1926, the Upper Lobau became a recreational place, whereas in the beginning an entrance fee had to be paid to access the still fenced area. This kind of cultural ecosystem service remains important in the Upper Lobau until nowadays (Eder & Eichert 2005).

The Lower Lobau was less affected by urban settlement expansion (Fig. 3). Around 1820, forests extended on 46 % of the total area, while aquatic habitats covered about 30 % and grasslands less than 14 %. Other land use types, such as arable land, were negligible. Typical soft wood tree species such as Poplar, Alder and Willows dominated. Forest management plans from the middle of the 20th century mention Grey Alder (*Alnus incana*), Black Poplar (*Populus nigra*) and Silver Poplar (*Populus alba*) (Forstoperat Untere Lobau 1947-1956). The trees provided mainly firewood, some hardwood trees were used for local hydraulic structures or various kinds of commodities. The Lower Lobau was an appreciated imperial hunting place where game was fostered.

The proportions of land use types changed only moderately during the 19th century. A moderate shift is noticeable after the Viennese Danube regulation. As the flood protection dikes prevented floods and thus hydromorphological dynamics, forests increased up to 61 %. In the period to come, decreasing groundwater tables and the lack of frequent surface inundation altered soil properties. This had an impact on the floodplain forests, where typical floodplain trees such as willows decreased. Despite the altered hydrology, human uses remained more or less the same until the middle of the 20th century.

In the 1950s, plans were developed to use groundwater from the Lower Lobau to supply Vienna with drinking water. Additionally, the growing agricultural production in the region Marchfeld east of Vienna showed an increasing demand for water. Starting with a few small wells for agriculture, an area of 10 km^2 was designated as drinking water protection zone. Groundwater works built in the 1960s served parts of Vienna east of the Danube with drinking water. Since 1988, the wells mainly secure the water supply of Vienna during peak demands and in case of maintenance work on the main water pipelines (Haidvogl et al. 2019).

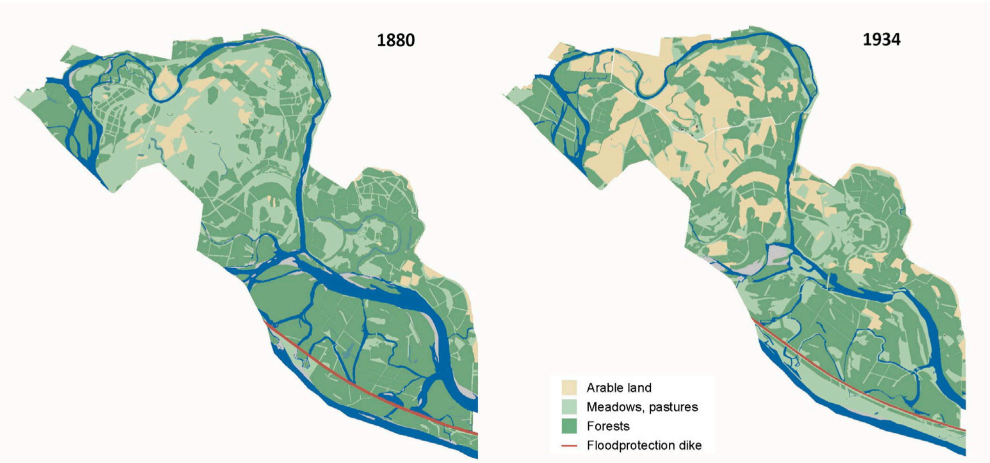

Fig. 3: Land use in the Lobau floodplains in 1880 (left) and 1934 (right). In contrast to the Upper Lobau, where arable land and grassland had increased to approx. 47 % at the expense of flood plain forests (24 %) by 1934, forests still dominated land use in the Lower Lobau. (Digitalization: Martin Perschl, Gertrud Haidvogl, visualization Friedrich Hauer, 2019). – Abb. 3: Landnutzung in der Lobau 1880 (links) und 1934 (rechts). Im Gegensatz zur Oberen Lobau, wo Acker- und Grünland bis 1934 auf Kosten der Auwälder (24 %) auf ca. 47 % zugenommen hatten, dominierte in der Unteren Lobau noch die Waldnutzung. (Digitalisierung: Martin Perschl, Gertrud Haidvogl, Visualisierung Friedrich Hauer, 2019).

Aquatic biodiversity and ecological functioning

Currently, the Lobau floodplain hosts a diverse flora and fauna with many species and habitat types of high protection status. Thus, the Lobau was designated as a site of European and International importance (NATURA 2000, UNESCO Men and Biosphere Reserve, RAMSAR) and is part of the Danube Floodplain National Park. Due to the high proportion of lentic water bodies, the macrophyte abundance and diversity has strongly increased since the Danube regulation (Baart et al. 2010). So far, up to 156 macrophyte species have been identified, with 82 of them having a protection status (Austrian Red Lists; Barta et al. 2009; Janauer 2005, 2006; Weigelhofer et al. 2014). Particularly small isolated water bodies in the Lower Lobau are biodiversity hot-spots hosting many rare and endangered aquatic plant species (Barta et al. 2009).

The Lower Lobau also contributes to the phyto- and zooplankton diversity of the National Park (Chaparro et al. 2018). Compared to more connected but equally impacted sections of the Danube, the Lobau shows a high diversity of microcrustaceans (Chaparro et al. 2019). These relatively large and slow-growing planktonic species show a high dominance in low-flowing and undisturbed habitats typical for the Lobau (Baranyi et al. 2002). With a total of 46 recorded dragonfly species, the Lower Lobau is the most species-rich floodplain in Austria (Schultz 2008; Schulze & Schneeweihs 2013). While the dragonfly fauna of the Lower Lobau is mostly dominated by generalists with a wide range of ecological requirements, endangered species, such as *Sympetrum meridionale*, *Somatochlora flavomaculata,* and *Orthetrum coerulescens,* can also be found. In addition, there are dragonfly species that are specialized in waters of different stages of sedimentation (e.g. *Leucorrhinia pectoralis,* protected according to the Habitats Directive, EC 1992) (Weigelhofer et al. 2014). Furthermore, 73 caddisfly species are known from the Lobau, which represents about 20 % of the total fauna of Austria and underlines the status of a high biodiversity hot spot. One caddisfly species, *Orthotrichia angustella*, was newly recorded for Austria. In addition to some widespread and common species, some specialties such as the bog-affine *Erotesis baltica* were found for the first time in eastern Austria, and a number of rarities from the Hydroptilidae family, such as *Hydroptila dampfi, H. simulans, H. pulchricornis, H. angustata, H. angulata* and *Oxyethira falcata,* were documented (Graf et al. 2012). With 50 % of all species detected, 36 species are listed in an endangerment category of the Austrian Red List (Malicky, 2009), with *Erotesis baltica* being classified as "Critically Endangered" in the highest endangerment category.

Regarding vertebrates, amphibia prefer small, fish-free, sun-exposed, and more or less vegetation-rich backwaters for reproduction, with *Rana dalmatina, Pelophylax spp.* and *Lissotriton vulgaris* also occurring in margin areas of the main secondary channel. Thus, isolated temporary backwaters with sufficiently long water permanence are important reproduction habitats for rare and protected amphibians such as the Danube Crested Newt (*Triturus dobrogicus*), the Fire-bellied Toad (*Bombina bombina*) and the European Common Spadefoot (*Pelobates fuscus*) (Schedl et al. 2009; Waringer-Löschenkohl et al. 1986, 2013). Furthermore, the Danube floodplains east of Vienna are the only reproduction areas of the European Pond Turtle (*Emys orbicularis*) in Austria (Korner et al. 2006), with about one third of the population found in the Lobau (Schindler et al. 2012). The fish community of the Lower Lobau is dominated by widely distributed eurytopic fish species. Rare, endangered and protected stagnophilic species can be found in less frequently connected (European Bitterling, *Rhodeus amarus*) or completely isolated waterbodies (e.g. Weatherfish, *Misgurnus fossilis*) (Schabuss & Reckendorfer 2006; Funk et al. 2013). In contrast, endangered rheophilic species (e.g. Nase, *Chondrostoma nasus* and Barbel, *Barbus barbus*) (Schabuss & Reckendorfer 2006) can only be found in and close to the dynamic connection to the Danube (Schabuss et al. 2013). The extensive reed belts of the Lobau offer habitats for reed-breeding waterbirds, such as the Little Bittern (*Ixobrychus minutus*) and the

Great Reed Warbler (*Acrocephalus arundinaceus*) (Schulze & Schütz 2013), which reach higher densities in the Lobau than in other floodplains of the Danube Floodplain National Park (Frühauf & Sabathy 2006). The large waterbodies with their extensive sedimentation zones offer habitat for wading birds, such as different species of herons (e.g. *Ardea alba*), or swimming water birds, such as several protected duck species (e.g. *Anas querquedula* or *Aythya ferina*) (Frühauf & Sabathy 2006).

An important element of river floodplains is their shallow (meters to tens of meters deep) alluvial groundwater systems. They not only fulfill an important ecosystem service in terms of water and nutrient retention (Griebler & Avramov 2015), but are habitats densely colonized by microorganisms and invertebrates. In fact, it is the proximity to the surface lotic environment (as a source of energy) and the dynamic hydrological conditions that make them essential natural bioreactors and hot-spots of groundwater biodiversity. For Europe, a high hypogean biodiversity could be shown for individual sections of the alluvial aquifers and floodplains of the Rhone, the Rhine, and the Danube River (Dole-Olivier et al. 1994; Pospisil 1994). The Lobau, and in particular the Lower Lobau, as part of the Danube Floodplain National Park, is among the world hot-spots of groundwater fauna biodiversity (Danielopol & Pospisil 2001, Griebler et al. 2023). In the area of the early UNESCO biosphere reserve Lower Lobau, groundwater ecological research started in 1975 (Danielopol 1976, 1984, 1989, 1991; Pospisil 1994) with not less than 35 stygobiont invertebrate taxa recorded until the year 2000 (Danielopol & Pospisil 2001). Recently, after a pause of 20 years, groundwater ecological research in the Lobau has been revived underlining the biodiversity hot-spot status of the Lower Lobau (see Griebler et al. 2023).

Predictions for the future ecological development based on the business as usual scenario

A "business-as-usual" scenario (S0 = no extra water supply to the Lower Lobau) was modelled based on the development of the floodplain over the past 70 years which predicted further aquatic habitat losses by almost 20 % until 2050 (Böttiger 2011, Weigelhofer et al. 2020). Losses can be even higher as the model does not consider any changes in the hydrological conditions of the Danube due to climate change. Especially existing shallow and isolated water bodies are threatened, with severe consequences for the respective fauna, such as stagnophilic dragonflies (e.g. *Leucorrhinia pectoralis, Lestes barbarus, Sympetrum meridionale*), and amphibia (Funk et al. 2013; Weigelhofer et al. 2020). However, while main reproduction areas for amphibia, such as Göthenwasser and Hanslgrund (Fig. 4), may dry out in the future, the increased fragmentation of the main secondary channel can create new habitats in the meantime. In contrast, *Emys orbicularis* needs less frequently connected but deeper water bodies for winter survival (e.g. Eberschüttwasser, Schwarzes Loch, Fig. 4) which will gradually disappear if water levels further decrease. These expected changes in the aquatic habitat mosaic need to be checked with empirical data and underlines the current water deficit. A further fragmentation of the main secondary channel and decreasing water levels during prolonged summer droughts will affect the eurytopic and rheophilic fish fauna negatively, especially when the connectivity to the Danube is further disrupted (Weigelhofer et al. 2020). Currently, the Lower Lobau does not provide habitats for endangered rheophilic Danube fish (e.g. Nase, *Chondrostoma nasus* and Barbel, *Barbus barbus*) (Schabuss & Reckendorfer 2006). Regarding the

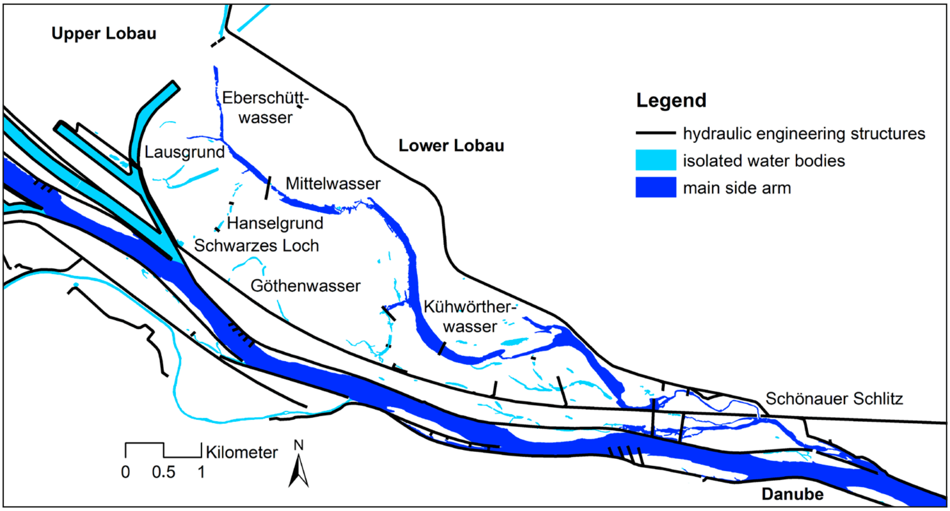

Fig. 4: Overview map of the Lobau with the sections Upper Lobau, Lower Lobau and their key areas. Isolated water bodies are labeled in light blue, the main secondary channel in dark blue. Black lines are indicating hydraulic engineering structures. – Abb. 4: Übersichtskarte der Lobau mit den Abschnitten Obere Lobau, Untere Lobau und deren Schlüsselbereichen. Isolierte Gewässer sind hellblau, der Hauptnebenarm dunkelblau eingezeichnet. Schwarze Linien weisen auf wasserbauliche Strukturen hin.

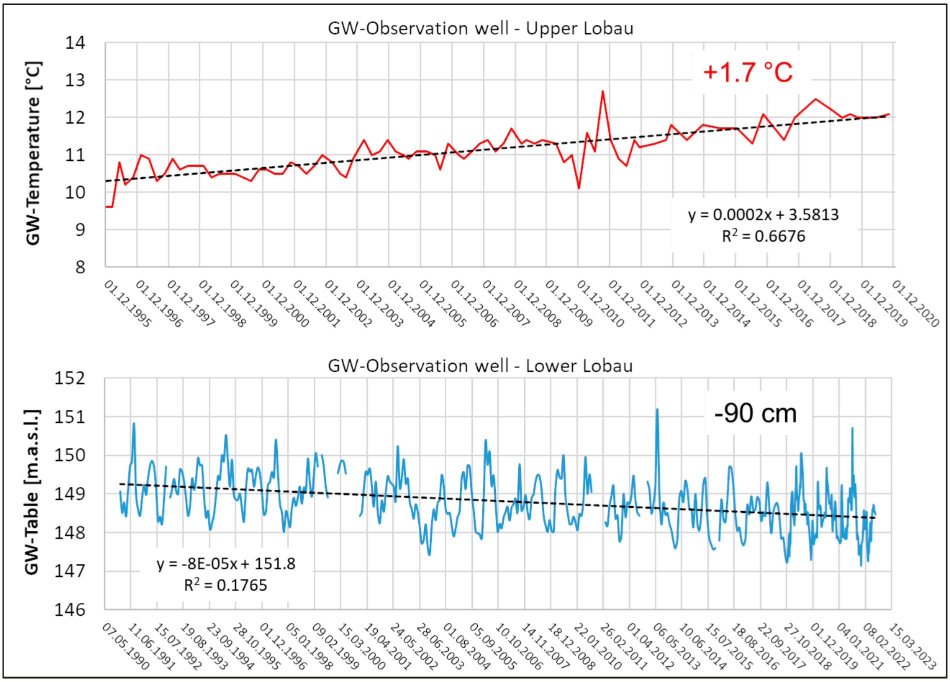

Fig. 5: 30 years trends of groundwater temperature and groundwater level at two monitoring wells located in the Upper and Lower Lobau. – Abb. 5: 30-jährige Entwicklung der Grundwassertemperatur und des Grundwasserspiegels an zwei Grundwassermessstellen in der Oberen und Unteren Lobau.

stagnophilic fish community only the Weatherfish *Misgurnus fossilis* may profit from the creation of new habitats in the course of further fragmentation. As reed zones will spread, reed-breeding birds will find more habitats for reproduction, especially those which prefer old reed stocks (Weigelhofer et al. 2020). However, reed-breeders that need dynamic areas with reed rejuvenation, such as the Great Reed Warbler, the Marsh Harrier, and the Great White Heron could suffer from habitat losses. The further extension of reed belts and the resulting increase in evapotranspiration will also aggravate the water deficits in the Lobau further (Weigelhofer et al. 2020).

The current trends of increasing groundwater temperatures in the entire Lobau and decreasing groundwater levels in the Lower Lobau (Fig. 5) may also pose a serious risk to groundwater biodiversity. While the temperature increase in the atmosphere and in surface water bodies is a global climate change phenomenon, the declining groundwater tables in the Lower Lobau are mainly caused by active water management decisions, i.e. prohibition of artificial surface water supply to the Lower Lobau justified by protective measures for drinking water production. Current data collected at individual spots in the Lower Lobau provide preliminary evidence that the timing and rhythm of maxima and minima in groundwater dissolved oxygen concentration and groundwater temperature have shifted (Griebler et al., unpubl. data). This pattern awaits systematic evaluation in the upcoming years.

Potential management scenarios for conservation and rehabilitation

Since the 1980s, various management concepts for a step-wise rehabilitation of the Lobau floodplain have been developed (Weigelhofer et al. 2013; Trauner et al. 2016). The overall aim of these concepts was the sustainable long-term protection of the current nature conservation state and the re-establishment of an increased hydrological dynamics of the secondary channels with the main channel (Fig. 4) of the Danube, considering the restoration potential of the respective sub-areas and local usages (e.g. tourism, drinking water supply). Due to its direct neighborhood to the city of Vienna and other smaller cities, a conservative approach was selected for the Upper Lobau. This approach mainly aimed at compensating the existing hydrological deficits, decreasing the water retention times in the main secondary channel to improve the self-purification capacity, protecting the established fauna and flora of lentic water bodies, and facilitating the establishment of rheophilic species in small lotic sections of the main secondary channel. Since 2001 water has been discharged from the New Danube and the Old Danube via the Mühlwasser into the Upper Lobau during the vegetation period (March to October), usually ranging between 0.2 to $0.4\,m^3\,s^{-1}$ discharge (Weigelhofer et al. 2011; Funk et al. 2009; Preiner et al. 2018). The New Danube as source of the water enhancement scheme was preferred over the Danube main channel due to the better and more predictable water quality. However, due to strict chemical, hygienic, and hydrological thresholds, less water than permitted ($0.5\,m^3s^{-1}$) has effectively flowed through the Upper Lobau so far. An additional water supply via a newly created pipeline from the New Danube into the oxbow lake “Panozzalacke” can increase the water input into the Upper Lobau with a maximum of $1.5\,m^3\,s^{-1}$ from 2023 onwards.

For the Lower Lobau, various hydrological management scenarios were developed aiming at a partial re-connection of the main secondary channel with the Danube and the establishment of lotic conditions over larger reaches to facilitate the migration and colonization of rheophilic species (Weigelhofer et al. 2020). The management scenarios in the study 2011 to 2015 comprised:

(1) a restricted water supply from the New Danube, ranging from 3 m^3s^{-1} to a maximum of 4.5 m^3 s^{-1} (S3) to improve the water exchange through the main secondary channel (constant water supply with low amounts) and

(2) a hydrologically more dynamic water supply of 20 m^3s^{-1} at Danube mean water (MW) levels (S20) to maximum peaks of up to 80 m^3s^{-1} during high flow conditions (at MW+ 1m) from the Danube, which creates lotic conditions along the entire main secondary channel and increases water levels in larger areas of the floodplain (Weigelhofer et al. 2020; Trauner et al. 2016). The channel network was adapted accordingly for the hydraulic modelling.

Based on the hydrological model and on habitat models (Funk et al. 2013), the potentially available habitats for the various protected species in the Lobau were estimated for the business-as-usual scenario S0 and the two management scenarios S3 and S20 until the year 2050 (Weigelhofer et al. 2020). To derive a prediction of the habitat availability in the different scenarios, species presence/absence data from the area of the whole National Park were modeled related to seven environmental parameters (upstream hydrological connectivity, downstream hydrological connectivity, sun exposure, maximal relative water depth at low, mean, and high water levels as well as water flow velocity at an annual flood event) using a generalized linearized model (GLM) approach described in Funk et al. (2013). Considering the actual distribution of species in the floodplain, the change in the potentially available habitats, and the respective conservation state, the three scenarios were ranked for the different species depending on their potential for improvement (5=good conservation status reached and further improvements; 4=good status reached, 3=good state not reached, but improvement), and deterioration (2=good state not reached, no habitat losses predicted; 1=good state not reached, further habitat losses predicted; for details, see Weigelhofer et al. 2020). The ranking was checked by experts of the National Park and the environmental protection agency via comparisons with other re-connected floodplains in the area and slightly adapted if necessary (e.g., in the case of over- or underestimations of the water flow velocity distribution).

The models predicted favorable conditions for the immigration and establishment of rheophilic macro-invertebrates in the lotic sections of the main secondary channel, while enough lentic habitats will remain for stagnophilic species. Similar observations have been made in the Upper Lobau (Funk et al. 2009). The improved water supply in the Lobau will create new isolated and shallow habitats in the currently dry areas which can be used by, e.g. stagnotopic dragonflies and amphibia as reproduction sites. These newly created habitats should compensate any losses of amphibian reproduction sites due to the increased hydrological connectivity and predatory pressure by fish (Waringer-Löschenkohl et al. 2013). Equally, the pond turtle *Emys orbicularis* should profit from the increase in both water areas and water depths. Thus, S3 and S20 scored equally high for most amphibians and the pond turtle, while the business-as-usual scenario S0 had the lowest score 1 (Weigelhofer et al. 2020; Fig. 6). Both reconnection scenarios (S3, S20) will change the potential habitat availability for macrophytes. The status quo is a shallow lake system offering favorable conditions for numerous macrophyte species. However, many of the currently diverse macrophyte habitats will get lost if the floodplain dries out further (S0). The controlled water

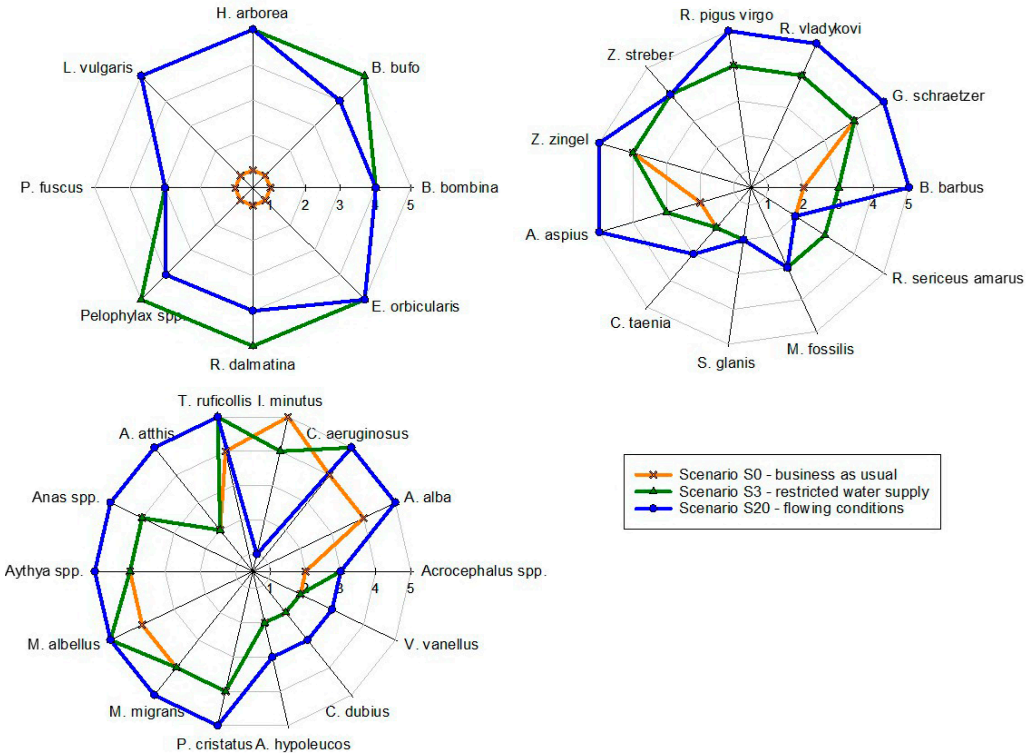

Fig. 6: Scores of the three hydrological scenarios for a: amphibia and the pond turtle, b: fish, and c: water birds depending on their potential for improvement (5=good conservation status reached and further improvements; 4=good status reached, 3=good state not reached, but improvement), and deterioration (2=good state not reached, no habitat losses predicted; 1=good state not reached, further habitat losses predicted) in the Viennese part of the Lobau. Species' full names: a: *Pelobates fuscus, Lissotriton vulgaris, Hyla arborea, Bufo bufo, Bombina bombina, Rana dalmatina; Emys orbicularis*; b: *Rutilus pigus virgo, Romanogobio vladykovi, Gymnocephalus schraetzer, Barbus barbus, Rhodeus sericeus amarus, Misgurnus fossilis, Silurnus glanis, Cobitis taenia, Aspius aspius, Zingel zingel, Zingel streber*; c: *Alcedo atthis, Tachybaptus ruficollis, Ixobrychus minutus, Circus aeruginosus, Ardea alba, Vanellus vanellus, Charadrius dubius, Actitis hypoleucos, Podiceps cristatus, Milvus migrans, Mergellus albellus*. – Abb. 6: Bewertungen der drei hydrologischen Szenarien für a: Amphibien und Sumpfschildkröte, b: Fische und c: Wasservögel in Abhängigkeit vom Verbesserungspotenzial (5=guter Erhaltungszustand erreicht und zusätzliche Verbesserungen; 4=guter Zustand erreicht, 3=guter Zustand nicht erreicht, aber Verbesserung) und Verschlechterung (2=guter Zustand nicht erreicht, keine Lebensraumverluste vorhergesagt; 1=guter Zustand nicht erreicht, weitere Lebensraumverluste vorhergesagt) im Wiener Teil der Lobau. Vollständige Namen der Arten: a: *Pelobates fuscus, Lissotriton vulgaris, Hyla arborea, Bufo bufo, Bombina bombina, Rana dalmatina; Emys orbicularis;* b: *Rutilus pigus virgo, Romanogobio vladykovi, Gymnocephalus schraetzer, Barbus barbus, Rhodeus sericeus amarus, Misgurnus fossilis, Silurnus glanis, Cobitis taenia, Aspius aspius, Zingel zingel, Zingel streber;* c: *Alcedo atthis, Tachybaptus ruficollis, Ixobrychus minutus, Circus aeruginosus, Ardea alba, Vanellus vanellus, Charadrius dubius, Actitis hypoleucos, Podiceps cristatus, Milvus migrans, Mergellus albellus.*

supply in S3 will increase the proportion of both shallow margin areas and deeper water bodies (important for submerged macrophytes) leading to improved habitat availability. In contrast, locally increased flow velocities in the main secondary channel are expected to lead to decreased macrophyte coverage and species numbers in those stretches (Baart et al. 2010; Trauner et al. 2016; Preiner et al. 2020). This development will be more pronounced in the S20 scenario due to more extended lotic sections.

In general, fish were expected to be positively affected by both S3 and S20 scenarios due to deeper water bodies and an increased connectivity among existing habitats (Fig. 6; Weigelhofer et al. 2020). These model predictions are supported by findings from other re-connection projects in adjacent floodplains in Orth and Regelsbrunn (Schabuss & Reckendorfer 2006; Zweimüller 2004), where especially young fish used the in- and outflow areas of the re-connected secondary channels. The highest potential for habitat gains of rheophilic fish showed S20. However, comparisons with the estimated historical species distributions revealed that even the S20 scenario cannot establish conditions necessary for endangered, strongly rheophilic Danube fish species (Weigelhofer et al. 2020). Similar as amphibians, the stagnophilic species *Rhodeus sericeus amarus* and *Misgurnus fossilis* may slightly benefit from the creation of new habitats (S3). In general, the scenarios, including S0, were more balanced for fish than for amphibia as neither large habitat gains nor large losses were predicted for the future.

Birds which use large water bodies for swimming or preying on fish (e.g. *Podiceps cristatus, Alcedo atthis*, *Milvus migrans*) should benefit from the larger water areas and the potentially increased fish population in both management scenarios S3 and S20 (Fig. 6) (Frühauf & Sabathy 2006). For gravel-breeders, only S20 has the potential for enough hydrological dynamics to move sediments and create new habitats. Reed-breeding birds preferring young reed stocks (e.g. *Acrocephalus spp.*) will profit from both S3 and S20 due to the creation of new reed habitats and the resulting rejuvenation. In contrast, reed-breeders preferring old stocks (e.g. *Ixobrychus minutus*) may lose habitats in the S20 scenario. Observations during the wet year 1999 showed similar trends for water birds as our model predictions, with habitat gains for most species except those breeding in dry reed belts (Frühauf & Sabathy 2006).

The scenario analyses confirmed that the scenario S0 without any additional water inputs will have severe consequences for the Lower Lobau regarding both the future habitat size and the habitat mosaic of (semi-) aquatic habitats, severely impacting the overall aquatic species diversity including the occurrence of protected species (Weigelhofer et al. 2020). While the current climate crisis has not yet been included in the S0 scenario, it is apparent that the situation will deteriorate further.

The scenario S3 will increase surface and subsurface water levels and water areas without changing the overall environmental conditions of aquatic habitats (only localized lotic conditions established). Thus, S3 will mainly support already established habitats and species. The ongoing terrestrialization will not be stopped entirely but partly compensated by the increased water levels.

The scenario S20 will allow lotic conditions in larger parts of the main secondary channel and may support the re-introduction of rheophilic species (Trauner et al. 2016, Weigelhofer et al. 2020). While the increased flow velocities and the increased connectivity (and predation by fish) may reduce areas currently used by stagnophilic species, the increased water supply in the Lower Lobau entails the option for compensation measures, such as the creation of new shallow and isolated backwaters. Thus, this scenario has the highest potential for increasing the overall species diversity and initiating local geomorphic processes. The geomorphic template for this scenario was adapted to allow the discharge for the defined amounts, but no dynamic changes were included. These analyses do not include the groundwater fauna but it can be assumed that increased surface water levels, and subsequently higher groundwater levels, as well as more dynamic conditions would also show positive effects on the groundwater biodiversity of the Lobau.

Recommendations for a management approach to improve the ecological conditions of the Lower Lobau

Based on the findings from the presented as well as other studies and expert groups, the following recommendations can be given for the Lower Lobau to conserve and restore the aquatic biodiversity of this area while simultaneously maintaining other ecosystem services:

- Apply an adaptive management approach by giving the highest priority to the immediate compensation of the actual water deficits in the Lower Lobau water bodies and acquiring the knowledge needed to prepare the next steps. Each next implementation step needs to be supported by empirically gained, science-based evidence.

- Nominate an independent committee of experts that develops generally applicable, transparent evaluation criteria for the different ecosystem functions and ecosystem services, supervises the monitoring and assessment of the floodplain under the management measures already applied, and evaluates further management options for application. Urgent measures need to be taken to compensate the dramatic deficit in the surface water system in most upstream parts, based on scenarios already developed and based on the higher availability of water in the Upper Lobau.

- The effects of actual and new controlled water inputs allow to gain the needed knowledge base for next steps to mitigate water deficits in the whole floodplain, not only the most upstream parts. Update modelling results and integrate climate change effects and groundwater ecological aspects to assess the effects of further measures on the hydrological and ecological conditions of the floodplain.

- Further development of measures to achieve at least partly dynamic conditions for hydrological and ecological improvements. These measures need to consider the geomorphic conditions such as the high rate of sedimentation, the ecological habitat mosaic and human uses in the area, particularly drinking water production and recreational uses to be tested in model approaches and experimental settings.

- An integration of already identified stakeholders and representatives of the wider public should be considered in further planning processes.

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Literature

Baart I, Gschöpf C, Blaschke, A P, Preiner S, Hein T (2010) Prediction of potential macrophyte development in response to restoration measures in an urban riverine wetland. Aquatic Botany 93(3), 153–162. https://doi.org/10.1016/j.aquabot.2010.06.002

Baranyi C, Hein T, Holarek C, Keckeis S, Schiemer F (2002) Zooplankton biomass and community structure in a Danube River floodplain system: effects of hydrology. Freshwater Biology 47(3), 473–482. https://doi.org/10.1046/j.1365-2427.2002.00822.x

Barta V, Schmidt-Mumm U, Janauer G A (2009) Adapting floodplain connectivity conditions–a prerequisite for sustaining aquatic macrophyte diversity in the UNESCO Biosphere Reserve Lobau (Austria). Ecohydrology & Hydrobiology 9(1), 73–81. https://doi.org/10.2478/v10104-009-0037-5

Chaparro G, Horváth Z, O'Farrell I, Ptacnik R, Hein T (2018) Plankton metacommunities in floodplain wetlands under contrasting hydrological conditions. Freshwater Biology 63(4), 380–391. https://doi.org/10.1111/fwb.13076

Chaparro G, O'Farrell I, Hein T (2019) Multi-scale analysis of functional plankton diversity in floodplain wetlands: Effects of river regulation. Science of the Total Environment 667, 338–347. https://doi.org/10.1016/j.scitotenv.2019.02.147

Council of the European Communities (1992) "Council Directive 92/43/EEC of 21March 1992 on the conservation of natural habitats and wild fauna and flora," Official Journal of the European Union L206 (Brussels: CEC), 7–50

Danielopol D L (1976) The distribution of the fauna in the interstitial habitats of riverine sediments of the Danube and the Piesting (Austria). International Journal of Speleology 8, 23–51. http://dx.doi.org/10.5038/1827-806X.8.1.3

Danielopol D L (1984) Ecological investigations on the alluvial sediments of the Danube in the Vienna area—a phreatobiological project. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen 22(3), 1755–1761. https://doi.org/10.1080/03680770.1983.11897571

Danielopol D L (1989) Groundwater fauna associated with riverine aquifers. Journal of the North American Benthological Society 8(1), 18–35. https://doi.org/10.2307/1467399

Danielopol D L (1991) Spatial-distribution and dispersal of interstitial Crustacea in alluvial sediments of a backwater of the Danube at Vienna. Stygologia 6(2), 97–110

Danielopol D L, Pospisil P (2001) Hidden biodiversity in the groundwater of the Danube flood plain national park (Austria). Biodiversity & Conservation 10(10), 1711–1721. https://doi.org/10.1023/A:1012098706986

Dole-Olivier M J, Marmonier P, Creuzé des Châtelliers M, Martin D (1994) Interstitial fauna associated with the alluvial flood plains of the Rhône River. In: Gibert J, Danielopol D L, Stanford J A (Eds), Groundwater Ecology, 313–346. Academic Press, San Diego, California

Donau-Regulierungs-Commission (1850) Die Regulierung der Donau und der Bau einer stabilen Brücke über dieselbe bei Wien. Sonderabdruck aus der Allgemeinen Bauzeitung 15, 41–137

Eberstaller-Fleischanderl D, Hohensinner S, Jungwirth M (2004) Donau 1726–2001. Flussmorphologische Entwicklung der Donau im Wiener Teil des Nationalparks Donau-Auen 1726–2001 (Bereich Lobau, Strom-km 1924,4–1907,6). Report to MA 49, City administration of Vienna

Eder G, Eichert R, (2005) Trockenzeiten, die Wiener Lobau als Schutzgebiet, In: Umwelt Stadt, Geschichte des Natur- und Lebensraumes Wien. Brunner K, Schneider P (Hrsg.), Böhlau Verlag Wien – Köln –Weimar. S. 360–373

Forstoperat Untere Lobau 1947-1956, Wirtschaftschaftbezirk Mühlleithen. Unpublished manuscript, Österreichische Bundesforste

Funk A, Reckendorfer W, Kucera-Hirzinger V, Raab R, Schiemer F (2009) Aquatic diversity in a former floodplain: remediation in an urban context. Ecological Engeneering 35, 1476–1484. https://doi.org/10.1016/j.ecoleng.2009.06.013

Funk A, Gschöpf C, Blaschke A P, Weigelhofer, G, Reckendorfer, W (2013) Ecological niche models for the evaluation of management options in an urban floodplain—conservation vs. restoration purposes. Environmental Science & Policy 34, 79–91. https://doi.org/10.1016/j.envsci.2012.08.011

Funk A, Weigelhofer G, Feldbacher E, Hein T (2014) Nullvariante – Hydromorphologische Modellierung. Bericht im Rahmen des Projekts Gewässervernetzung (Neue) Donau – Untere Lobau (Nationalpark Donauauen). Report for MA 45, City Administration of Vienna

Funk A, Martínez-López J, Borgwardt F, Trauner D, Bagstad K J, Balbi S, Magrach A, Villa F, Hein T (2019) Identification of conservation and restoration priority areas in the Danube River based on the multi-functionality of river-floodplain systems. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2018.10.322

Funk A, Tschikof M, Grüner B, Böck K, Hein T, Bondar-Kunze E (2021) Analysing the potential to restore the multi-functionality of floodplain systems by considering ecosystem service quality, quantity and trade-offs. River Research and Applications 37(2) 221–232. https://doi.org/10.1002/rra.3662

Frühauf J, Sabathy E (2006) Untersuchungen an Schilf- und Wasservögeln in der Unteren Lobau. Teil I: Bestände und Habitat. Report for Nationalpark Donau-Auen GmbH as part of the LIFE -project Gewässervernetzung und Lebensraummanagement Donauauen

Graf W, Leitner P, Hohensinner S (2012) Gewässervernetzung (Neue) Donau – Untere Lobau (Nationalpark Donau-Auen): Erhebung der Trichoptera 2011. Report for MA 45, City Administration of Vienna

Graf W, Chovanec A, Hohensinner S, Leitner P, Schmidt-Kloiber A, Stubauer I, Waringer J, Ofenböck G (2013) Das Makrozoobenthos als Indikatorgruppe zur Bewertung großer Flüsse unter Einbeziehung auenökologischer Aspekte. Österreichische Wasser- und Abfallwirtschaft 65, 386–399. https://doi.org/10.1007/s00506-013-0117-z

Griebler C, Avramov M (2015) Groundwater ecosystem services – a review. Freshwater Science 34, 355–367. https://doi.org/10.1086/679903

Griebler C, Karwautz C, Rasch G, Fillinger L, Veits R, Junker R, Gaviria S, Fuchs A, Scharhauser F, Eisendle U, Steger J, Greilhuber M, Schiemer F, Pfingstl T, Pospisil P, Danielopol D L (2023) The Lobau and Danube Flood Plain National Park revisited – current inventory of a world hotspot of groundwater fauna biodiversity. Acta ZooBot Austria, this issue

Habersack H, Hein T, Stanica A, Liska I, Mair R, Jäger E, Hauer C, Bradley C (2016) Challenges of river basin management: Current status of, and prospects for, the River Danube from a river engineering perspective. Science of the Total Environment 543, pp. 828–845. https://doi.org/10.1016/j.scitotenv.2015.10.123

Haidvogl G (2023) The history of the Lobau in the 19th and 20th century: Land use change, diversification of human uses and long-term conflicts between conservation and utilization. Acta ZooBot Austria 159, 5–19

Haidvogl G, Hauer F, Hohensinner S, Raith E, Schmid M, Sonnlechner C, Spitzbart-Glasl C, Winiwarter V (2019) Wasser Stadt Wien: Eine Umweltgeschichte. Zentrum für Umweltgeschichte Wien (ZUG)

Hein T, Schwarz U, Habersack H, Nichersu I, Preiner S, Willby N, Weigelhofer G (2016) Current status and restoration options for floodplains along the Danube River. Science of the Total Environment 543, 778–790. https://doi.org/10.1016/j.scitotenv.2015.09.073

Hohensinner S, Eberstaller-Fleischanderl D, Haidvogl G, Herrnegger M, Weiß M (2008) Die Stadt und der Strom – Historische Veränderungen der Wiener Donau-Auen seit dem 18. Jahrhundert. Abhandlungen der Geologischen Bundesanstalt 62, 87–93

Hohensinner S, Jungwirth M (2009) Hydromorphological characteristics of the Danube River – the historical perspective. Österreichische Ingenieur- u. Architekten-Zeitschrift 154 (1-6), 33–38

Hohensinner S, Jungwirth M, Muhar S, Schmutz S (2011) Spatio-temporal habitat dynamics in a changing Danube river landscape 1812-2006. River Research and Applications 27 (8), 939–955. https://doi.org/10.1002/rra.1407

Hohensinner S, Grupe S, Klasz G, Payer T (2022) Long-term deposition of fine sediments in Vienna's Danube floodplain before and after channelization. Geomorphology 398, 108038. https://ssrn.com/abstract=3923538

Hohensinner S, Pöppl R (2022) The Danube Floodplain National Park: A Fluvial Landscape with Expiration Date? In: Landscapes and Landforms of Austria. Cham: Springer International Publishing, 2022, 193–206

ICPDR (2021) Danube River Basin Management Plan 2021. IC–231. Vienna, Austria. International Commission for the Protection of the Danube River, p. 251. Available at: https://www.icpdr.org/main/publications/danube-river-basin-management-plan-drbmp-update-2021 (Accessed: 24 November 2022)

Janauer G A (2005) Aquatic habitats in Vienna (Austria) – integrating ecology and urban water management. Ecohydrology and Hydrobiology 5, 279–284

Janauer G A (2006) Ecohydrological control of macrophytes in floodplain lakes. Ecohydrology and Hydrobiology 6, 19–24. https://doi.org/10.1016/S1642-3593(06)70122-7

Kling H, Fuchs M, Paulin M (2012) Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. Journal of Hydrology 424, 264–277. https://doi.org/10.1016/j.jhydrol.2012.01.011

Korner I, Reckendorfer W, Semrad J, Groiss M, Mair B, Reiter K, Rötzer H, Staudinger M (2006) Fachbeitrag Naturschutz / Biotopschutz Naturverträglichkeitserklärung, Teil 1, FFH-Arten und Lebensraumtypen. In: Umweltverträglichkeitserklärung Flussbauliches Gesamtprojekt Donau östlich von Wien

Lorenzo C (1819) Nieder Oesterreichische Donau–Stromkarte, M: 1:7200, surveyed 1816–1817, published 1819, 69 maps, Provincial Library of Lower Austria, Sign. B II 82

Malicky H (2009) Rote Liste der Köcherfliegen Österreichs (Insecta: Trichoptera). In: Zulka K P (Ed.), Rote Listen gefährdeter Tiere Österreichs. Checklisten, Gefährdungsanalysen, Handlungsbedarf. Teil 3: Flusskrebse, Köcherfliegen, Skorpione, Weberknechte, Zikaden. Herausgegeben von Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft 14(3), 319–359

Nanson G C, Croke J C (1992) A genetic classification of floodplains. Geomorphology 4, 459–486. https://doi.org/10.1016/0169-555X(92)90039-Q

Nanson G C, Knighton A D (1996) Anabranching rivers: their cause, character and classification. Earth Surface Processes and Landforms 21, 217–239. https://doi.org/10.1002/(SICI)1096-9837(199603)21:3<217::AID-ESP611>3.0.CO;2-U

Pospisil P (1994) The groundwater fauna of a Danube aquifer in the "Lobau" wetland in Vienna, Austria. In: Gibert J, Danielopol D L, Stanford J A (Eds), Groundwater Ecology 347–366. Academic Press, San Diego, California

Preiner S, Weigelhofer G, Funk A, Hohensinner S, Reckendorfer W, Schiemer F, Hein T (2018) Danube Floodplain Lobau. In: Schmutz S, Sendzimir J. (Eds): Riverine ecosystem management: Science for governing towards a sustainable future. Aquatic Ecology Series Vol. 8. Springer, Cham 491–506. https://doi.org/10.1007/978-3-319-73250-3, ISBN 978-3-319-73250-3

Preiner S, Dai Y, Pucher M, Reitsema R E, Schoelynck J, Meire P, Hein T (2020) Effects of macrophytes on ecosystem metabolism and net nutrient uptake in a groundwater fed lowland river. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2020.137620

Reckendorfer W, Funk A, Gschöpf C, Hein T, Schiemer F (2013) Aquatic ecosystem functions of an isolated floodplain and their implications for flood retention and management. Journal of Applied Ecology 2013, 50, 119–128. https://doi.org/10.1111/1365-2664.12029

Sanon S, Hein T, Douven W, Winkler P (2012) Quantifying ecosystem service trade-offs: The case of an urban floodplain in Vienna, Austria. Journal of Environmental Management 111, 159–172. https://doi.org/10.1016/j.jenvman.2012.06.008

Schabuss M, Reckendorfer W (2006) Die Hydrologie als Schlüsselparameter für die Verteilung der Adult- und Jungfischfauna im Altarmsystem der Unteren Lobau. Report for Nationalpark Donauauen GmbH, Wissenschaftliche Reihe 12

Schabuss M, Zornig H, Hricova R (2013) Die Fischfauna der Unteren Lobau – Ergebnisse der Erhebungen aus dem Jahr 2012. Gewässervernetzung (Neue) Donau – Untere Lobau (Nationalpark Donau-Auen). Report for MA 45, City Administration of Vienna

Schabuss M, Zornig H, Hricova R, Reckendorfer W (2013) Erhebung der Fischfauna im Nördlichen und Südlichen Lausgrund 2012. Gewässervernetzung (Neue) Donau – Untere Lobau (Nationalpark Donau-Auen). Report for MA 45, City Administration of Vienna

Schedl H, Gollmann G, Pintar M (2009) Erhebung des Donaukammmolches (*Triturus dobrogicus*) in der Lobau. Report to MA 22, City Administration of Vienna

Schindler M, Schmidt M, Reckendorfer W (2012) Erhebung der Europäischen Sumpfschildkröte, Gewässervernetzung (Neue) Donau – Untere Lobau (Nationalpark Donau-Auen). Report for MA 45, City Administration of Vienna

Schultz H (2008) Erhebung der Libellenfauna der Unteren Lobau. In: Faunistische Beweissicherung Dotation Untere Lobau 2007. Erhebung der Libellen, Amphibien und Brutvögel mit Gewässerbindung, Bericht des Projekts Gewässervernetzung (Neue) Donau – Untere Lobau (Nationalpark Donau-Auen). Report for MA 45, City Administration of Vienna

Schulze C H, Schütz C (2013) Wissenschaftliche Beweissicherung Lausgrund: Erhebung der Brutvögel mit Gewässerbindung 2012. Bericht des Projekts Gewässervernetzung (Neue) Donau – Untere Lobau (Nationalpark Donau-Auen). Report for MA 45, City Administration of Vienna

Schulze C H, Schneeweihs S (2013) Die Libellen der unteren Lobau – Ergebnisse der Erhebungen aus dem Jahr 2012. Gewässervernetzung (Neue) Donau – Untere Lobau (Nationalpark Donau-Auen). Report for MA 45, City Administration of Vienna

Stammel B, Amtmann M, Gelhaus M, Cyffka B (2018) Change of regulating ecosystem services in the Danube floodplain over the past 150 years induced by land use change and human infrastructure. Erde, 149(2–3), 145–156. https://doi.org/10.12854/erde-2018-378

Tockner K, Stanford J A (2002) Riverine flood plains: present state and future trends. Environmental Conservation 29(3), 308–330. https://doi.org/10.1017/S037689290200022X

Tomscha S A, Gergel S E, Tomlinson M J (2017) The spatial organization of ecosystem services in river-floodplains. Ecosphere, 8(3), e01728. https://doi.org/10.1002/ecs2.1728

Trauner D, Funk A, Pölz E M, Feldbacher E, Weigelhofer G, Reckendorfer W, Hein T (2016) Integrierte gewässerökologische Modellansätze zur Beurteilung von Gewässervernetzungsvarianten am Beispiel der Unteren Lobau. Österreichische Wasser- und Abfallwirtschaft. https://doi.org/10.1007/s00506-016-0322-7

Tschikof M, Gericke A, Venohr M, Weigelhofer G, Bondar-Kunze E, Kaden U S, Hein T (2022) The potential of large floodplains to remove nitrate in river basins–The Danube case. Science of the Total Environment 843, 156879. https://doi.org/10.1016/j.scitotenv.2022.156879

Waringer-Löschenkohl A, Lengauer R, Schweiger E, Slapa C (1986) Aufnahme der Amphibienfauna in den Donauauen bei Schönau (Niederösterreich). Verhandlungen der Zoologisch-Botanischen Gesellschaft in Österreich 124, 115–120

Waringer-Löschenkohl A, Csarmann E, Ruzek S, Reckendorfer W (2013) Erhebung der Amphibien 2012, Report for MA 45, City Administration of Vienna

Weigelhofer G, Janac P, Hein T (2005) Erkenntnisse zur Ökologie aus dem Wasserwirtschaftlichen Versuch „Dotation Obere Lobau, Wien“ für eine nachhaltige Entwicklung urbaner Augewässer. Österreichische Wasser- und Abfallwirtschaft. 9–10, 16–19. https://doi.org/10.1007/BF03164452

Weigelhofer G, Hein T, Kucera-Hirzinger V, Zornig H, Schiemer F (2011) Hydrological improvement of a former floodplain in an urban area: Potential and limits. Ecological Engeneering 37(10), 1507–1514. https://doi.org/10.1016/j.ecoleng.2011.05.005

Weigelhofer G, Reckendorfer W, Funk A, Hein T (2013) Auenrevitalisierung - Potenzial und Grenzen am Beispiel der Lobau, Nationalpark Donau-Auen. Österreichische Wasser- und Abfallwirtschaft. https://doi.org/10.1007/s00506-013-0115-1

Weigelhofer G, Funk A, Feldbacher E, Hein T (2015) Nullvariante – Fachbericht im Rahmen des Projekts Gewässervernetzung (Neue) Donau – Untere Lobau (Nationalpark Donauauen). Report for MA 45, City Administration of Vienna

Weigelhofer G, Feldbacher E, Trauner D, Pölz E M, Hein T, Funk A (2020) Integrating conflicting goals of the EC water framework directive and the EC habitats directives into floodplain restoration schemes. Frontiers in Environmental Science 8, 538139. https://doi.org/10.3389/fenvs.2020.538139

Zweimüller I (2004) Der Einfluss der Öffnungsmaßnahmen auf die Fischfauna im Regelsbrunner Altarmsystem (The impact of restoration on the fish community of the “Regelsbrunner Au”). Abhandlungen der Zoologisch-Botanischen Gesellschaft in Österreich 34, 137–154

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